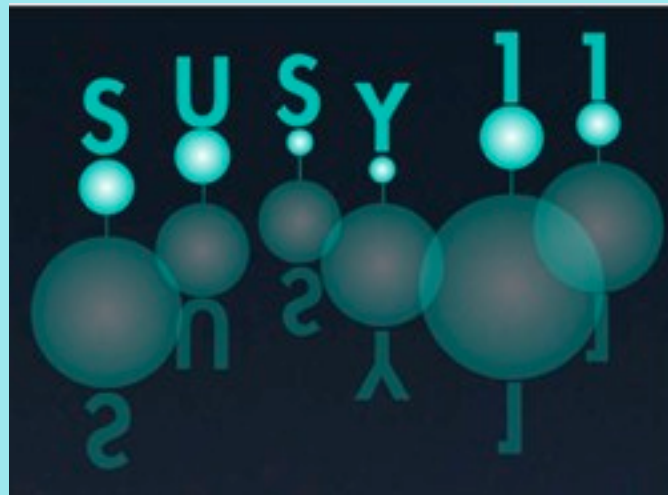


Searches for Heavy Resonances at DØ

Ioannis Katsanos

*University of Nebraska - Lincoln
for the DØ Collaboration*





Outline



- * Introduction
- * Theory
- * Tevatron - DØ Detector
- * Analyses
- * Limits
- * Summary and Conclusions



Introduction

What is a Z' ?



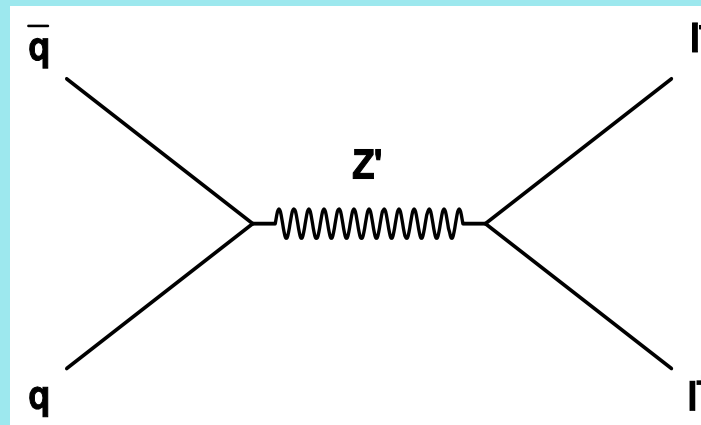
- * From a Theorist point of view
 - * A Z' is a “heavy” neutral gauge boson (spin 1)
 - * Examples can be a new $U(1)$ gauge boson; Kaluza-Klein modes of γ , Z , ...
- * From an Experimentalist’s point of view:
 - * A Z' is a “heavy” object which appears as a “narrow” resonance
 - * Examples can be extra gauge bosons; Randall-Sundrum KK gravitons; KK modes of γ , Z , ...; Exotic Higgses (eg in SUSY);...
- * Both points of view are valid, although it is important to define what we mean by “heavy” and “narrow” so we communicate better
 - * $Z' \Leftrightarrow$ Heavy Resonances
 - * “Heavy” \Rightarrow Above the reach of LEP (~ 200 GeV)
 - * “Narrow” \Rightarrow Natural width less than the detector (calorimeter) resolution



Theory

- * Various extensions of the Standard Model often postulate an additional U(1) group to its gauge structure ($SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$)
- * Additional group may arise in models derived from grand unified theories (GUT)
- * Gives rise to associated gauge bosons (commonly referred to as Z' bosons), which are electrical neutral, spin 1 particles
- * Such Z' bosons typically couple to SM fermions through electroweak interaction
- * Can be observed at hadron colliders as narrow resonances through the process

$$q\bar{q} \rightarrow Z' \rightarrow e^+e^-$$





Theory Z' Boson



- * Plethora of Z' models
- * One way to distinguish these models is by the strength of their coupling constants
- * If electroweak scale couplings, models are called “canonical”
 - * Sequential SM Z' boson
 - * Same couplings as SM Z boson
 - * Width $\Gamma_{Z'} = \Gamma_Z \times m_{Z'}/m_Z$ (for $M_{Z'} > 2m_t$ the decay channel to t-tbar opens)
 - * The E6 models: $E6 \rightarrow SO(10) \times U(1)_\psi$ and $SO(10) \rightarrow SU(5) \times U(1)_\chi$
 - * Gives rise to additional $Z'(\theta) = Z'_\chi \cos\theta + Z'_\psi \sin\theta$, where $0 \leq \theta < \pi$
 - * $Z'_\chi (\theta = 0)$ is a special case in another set of models (T_{3R} and B-L models)
- * Stuckelberg model: Example of a model with non-standard couplings (“non-canonical”) *PLB 586 (2004) 366*
 - * Gives rise to a very narrow Z' (for $M_{Z'} = 300 \text{ GeV}$, $\Gamma \sim 20 \text{ MeV}$)
 - * Parameters of model, mass mixing ε and $M_{Z'}$

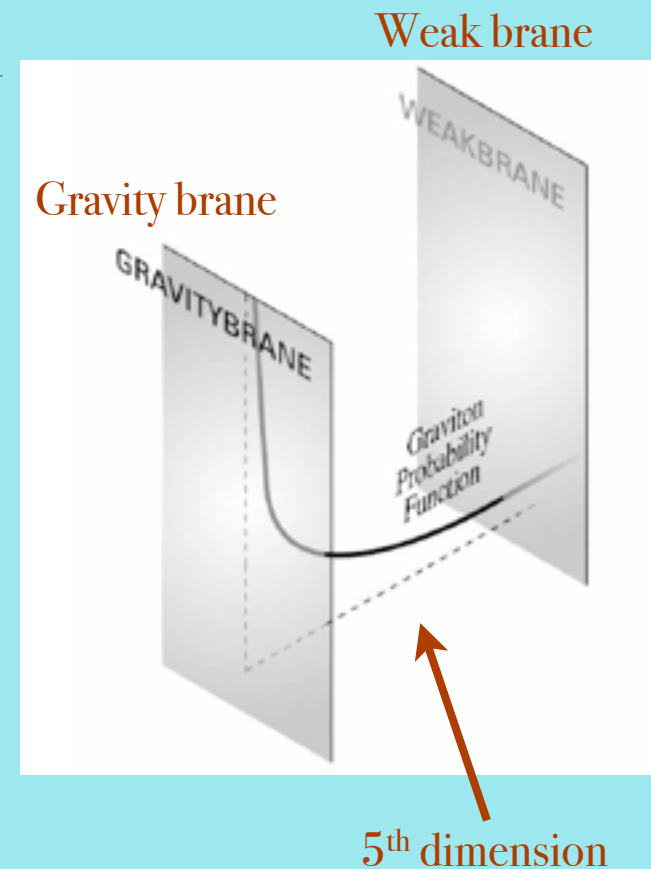


Theory

Randall - Sundrum Model

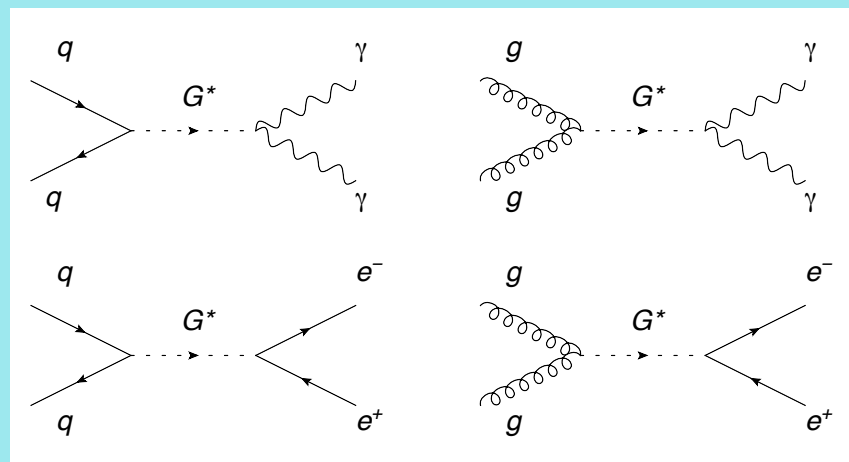


- * Randall - Sundrum Model (RS) describes a 5 dimensional warped geometry
- * SM fields: weak-brane; Gravity: gravity-brane
- * Any mass parameter M on the weak-brane yields to a physical mass M_0 in the higher dimensional theory
- * $M = M_0 \cdot e^{-kr\pi}$, where $e^{-kr\pi}$ is the warp factor, k is the curvature scale, and r ($=r_c$) is the compactification radius of the extra dimension
- * $kr_c = 11-12$ yields SM observed electroweak/gravity scale



- * Compactification of 5th dimension gives rise to KK gravitons (G^*)
- * The only particles that propagate in the 5th dimension
- * Spin 2
- * Universal coupling to SM fields
- * Parameters used
 - * Mass of lightest KK graviton M_1
 - * Dimensionless coupling constant k/\bar{M}_{Pl}
 - * $0.01 \leq \bar{k}/M_{Pl} \leq 0.1$

$$BR(\gamma\gamma)/BR(ee) = 2$$





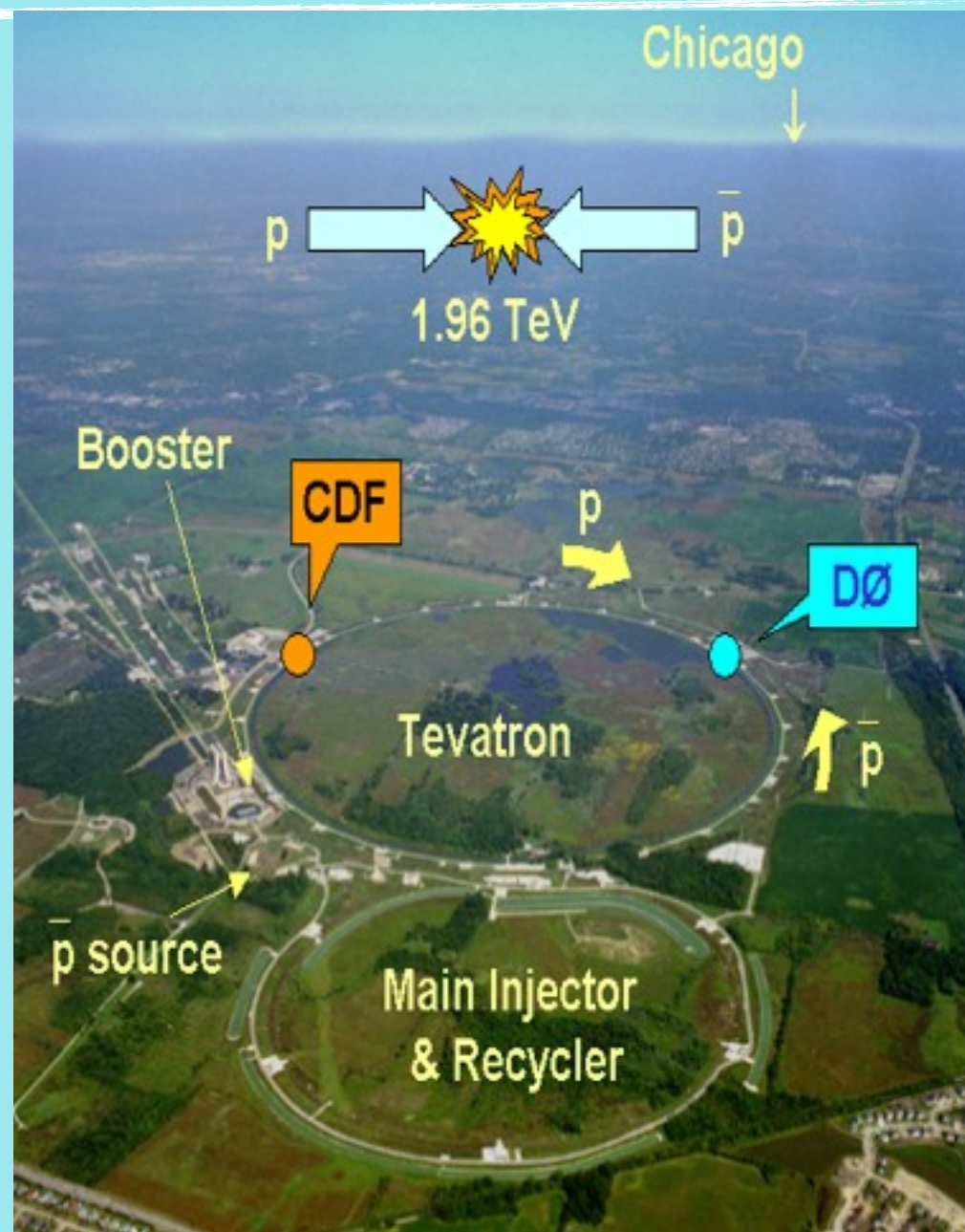
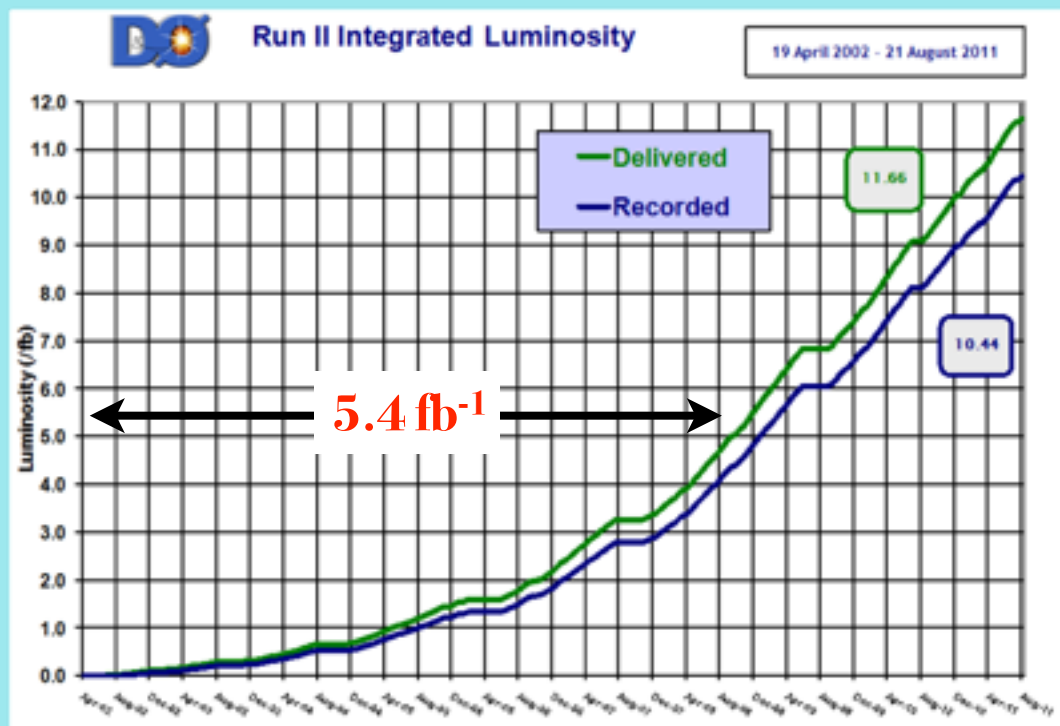
Instrumentation Accelerator and Detector



Fermilab Tevatron Collider



- * Proton-antiproton collider with 1.96 TeV center-of-mass energy
- * Single magnet ring - protons and antiprotons circulate in opposite directions
- * Close to 12 fb^{-1} delivered. More than 2 fb^{-1} per year delivered

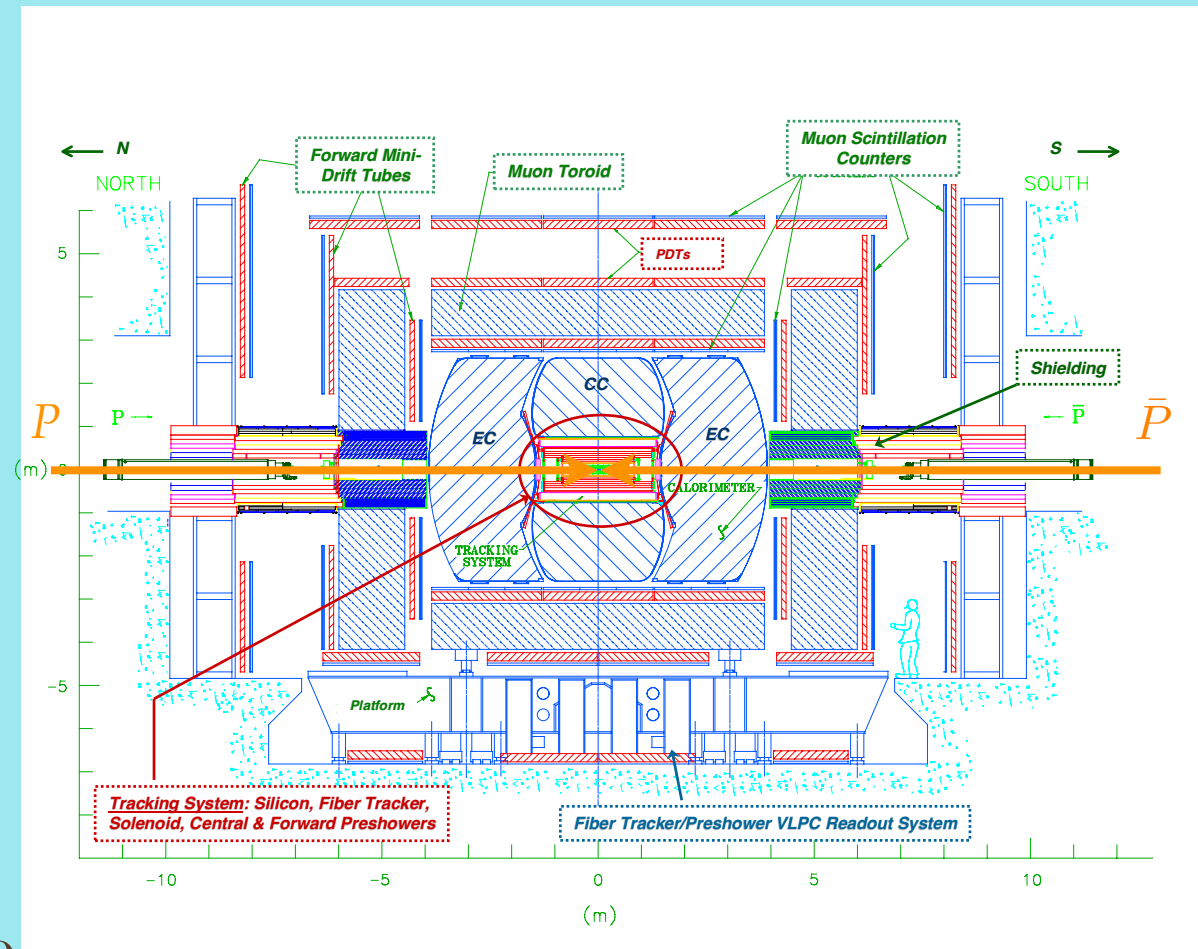




DØ Detector



- * General purpose detector
- * Tracking system
- * Calorimeter
- * Muon system
- * Coordinates system
- * Cylindrical with z along the beam axis
- * $\eta = -\ln[\tan(\theta/2)]$
- * p_T - Momentum transverse to the beam axis





ANALYSES



Analysis Strategy



- * Search for narrow resonances on the invariant mass spectra of ee and $\gamma\gamma$ decay channels
- * To optimize sensitivity and maintain flexibility, split the data into dielectron and diphoton samples based on tracking information
- * Derive contribution of each SM background by fitting to the data invariant mass spectrum in a control region around the Z peak
- * Normalize the background shapes to their contributions in the control region and extrapolate into the signal region
- * Search for excesses. In absence of a significant excess, proceed with setting limits

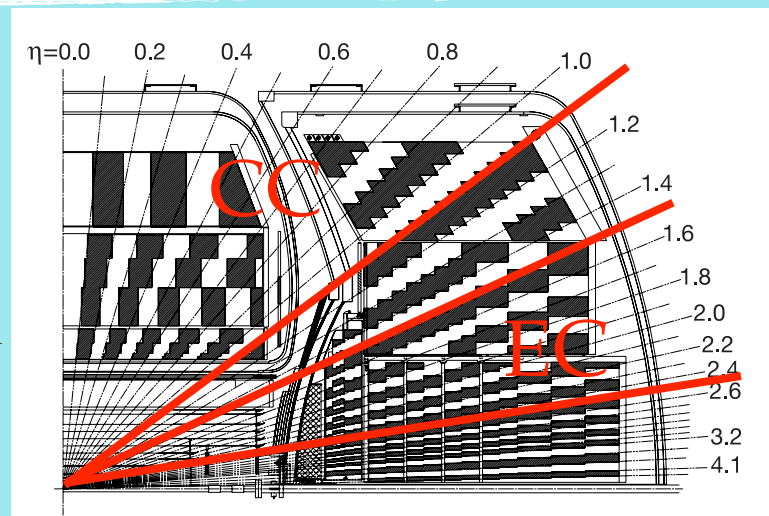


Data Selection

EM Objects Identification



- * Goal is to select EM objects and remove background
- * Sources of background:
 - * π^0 showers that can overlap with nearby track
 - * Charged pions
 - * Jet Fluctuations
- * EM particles are reconstructed using energy deposited at the four EM calorimeter layers and the first hadronic
- * EM objects need to have $p_T > 25 \text{ GeV}$ and $|\eta| < 1.1$
 - * Focus only in events where both objects are in Central Calorimeter. Adding objects in the End-Caps would improve by $\sim 2\%$ our sensitivity in the signal region, while having higher background contributions
 - * Select events with at least two EM objects
 - * Choose the two highest p_T EM objects





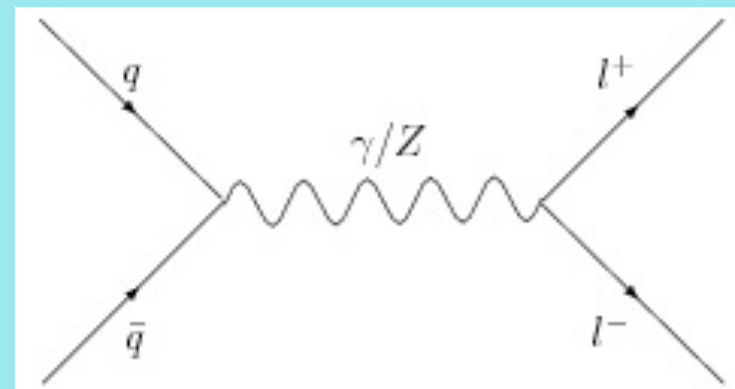
Data Selection

EM Objects Identification

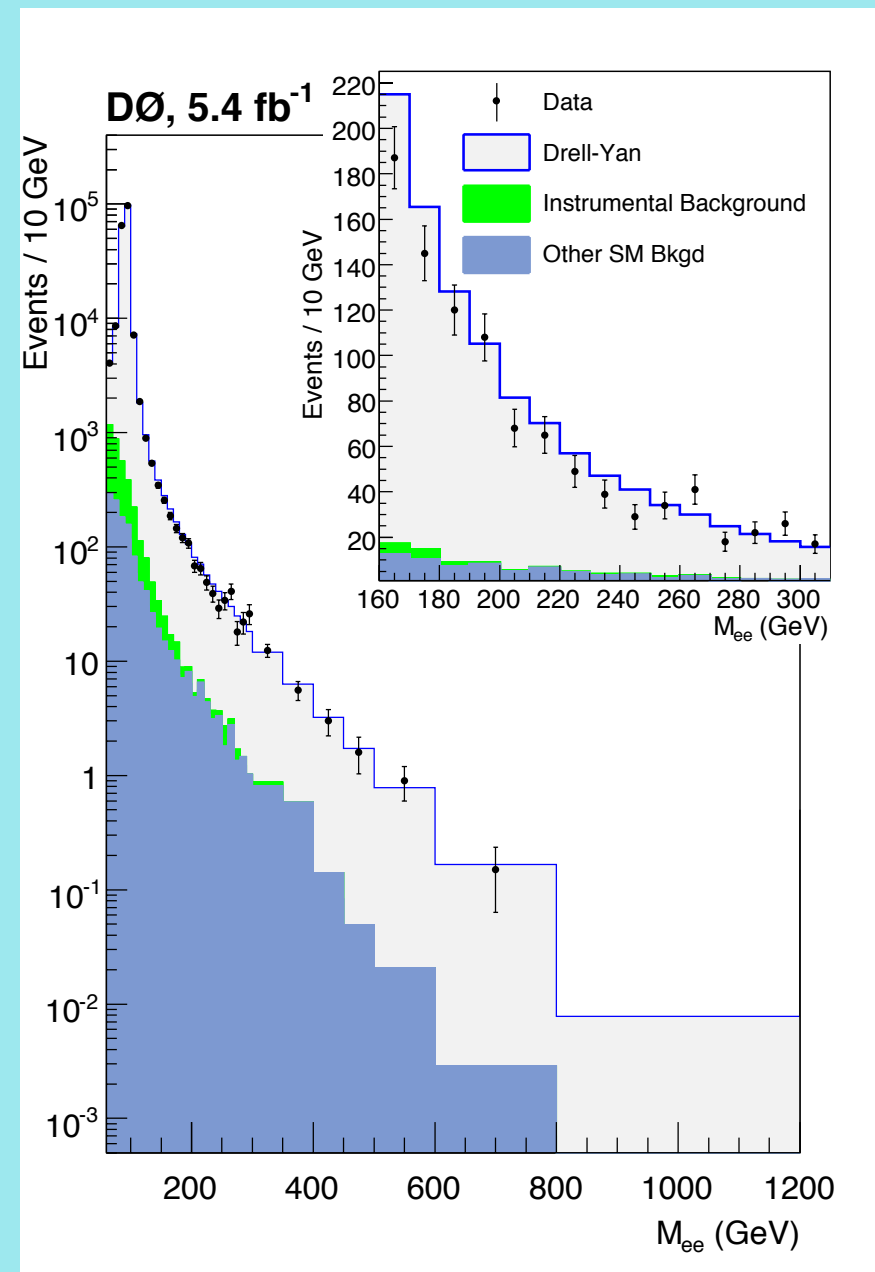


- * Both EM candidates are required to pass relatively “Loose” EM ID algorithm that uses calorimeter information
- * To be included in the dielectron sample **both** objects should pass track match requirements
- * No opposite charge requirement, due to increased charge misidentification in the signal region
- * To be included in the diphoton sample **at least one** object should fail the track match requirements

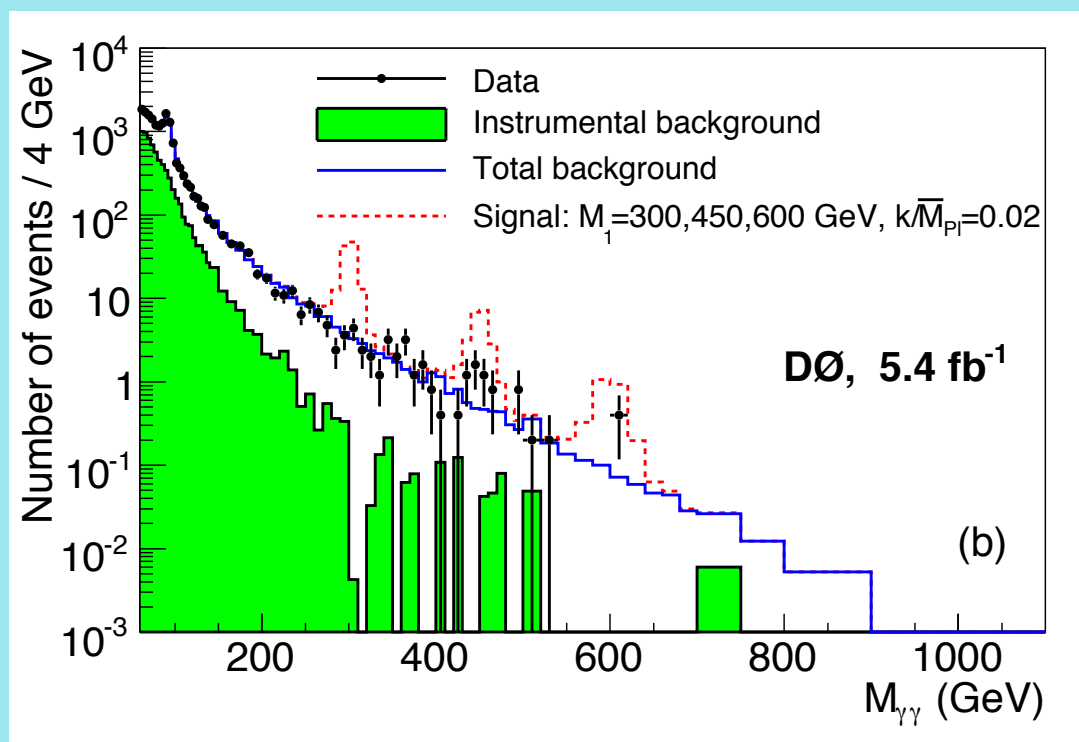
- * Physics backgrounds
 - * Drell-Yan ($Z/\gamma^* \rightarrow ee$)
 - * Main irreducible background
 - * SM $\gamma\gamma$ production
 - * “Other SM” background
 - * $Z/\gamma^* \rightarrow \tau\tau, W\gamma, WW, ZZ, WZ, W+\text{jets}, t\text{-}t\text{bar}$
 - * Studied in Monte Carlo using PYTHIA
- * Instrumental Background: Fake objects from QCD events
 - * Dielectron: Jet + Jet
 - * Diphoton: $\gamma + \text{Jet}$ and Jet + Jet
 - * Shape is estimated from data using a sample rich in misidentified EM objects
 - * Sample is acquired by inverting the calorimeter shower shape requirements



- * Having determined the background shapes, normalize the background to data in the low mass region
- * For the Z' search: $60 < M_{ee} < 150 \text{ GeV}$
- * For the RS search: $60 < M_{ee} < 200 \text{ GeV}$
- * Extrapolate normalizations to the full studied spectrum



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SETTING LIMITS



Systematic Uncertainties



* Statistically limited analysis

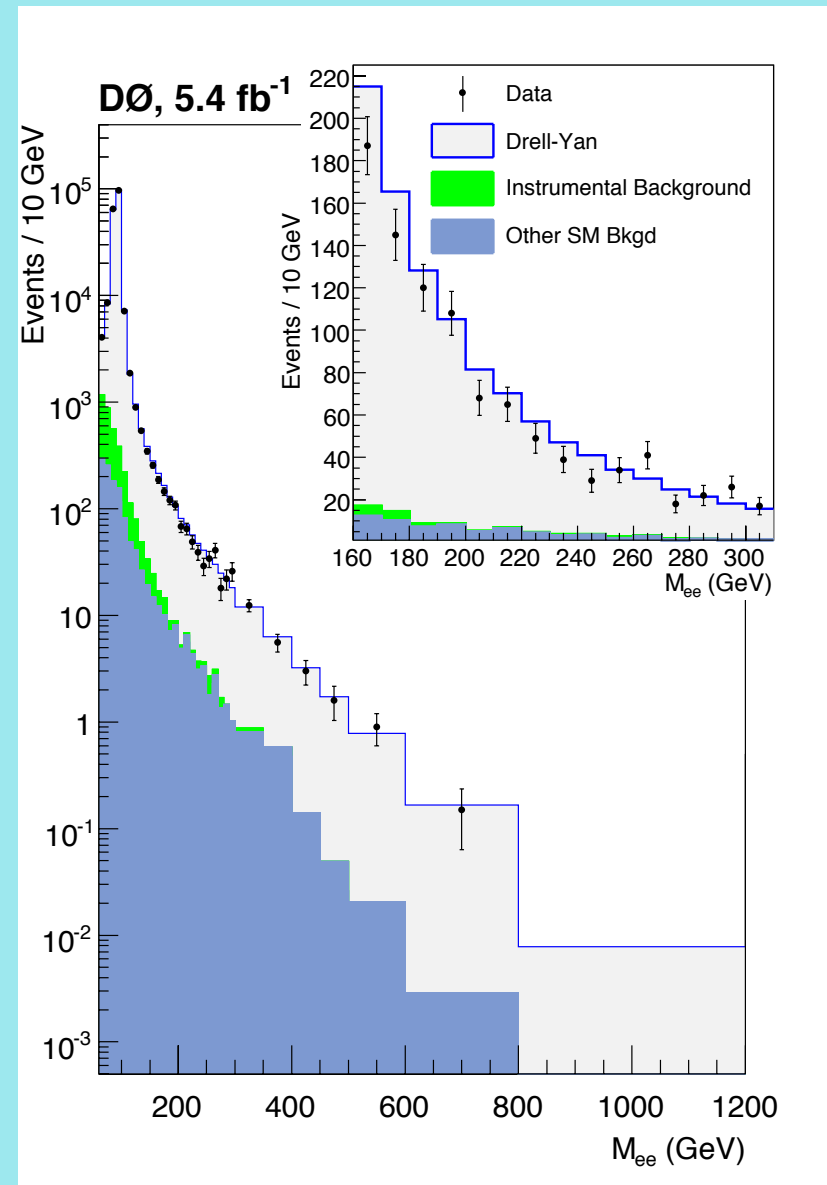
Signal

Luminosity	6.1%
ID Efficiency	3% per object
Signal Acceptance Uncertainty due to PDFs	0.4% - 7.6%
Signal Cross Section Uncertainty due to PDFs	3.4% - 17%
EM Energy Resolution	6%
Trigger Efficiency	0.1%

Background

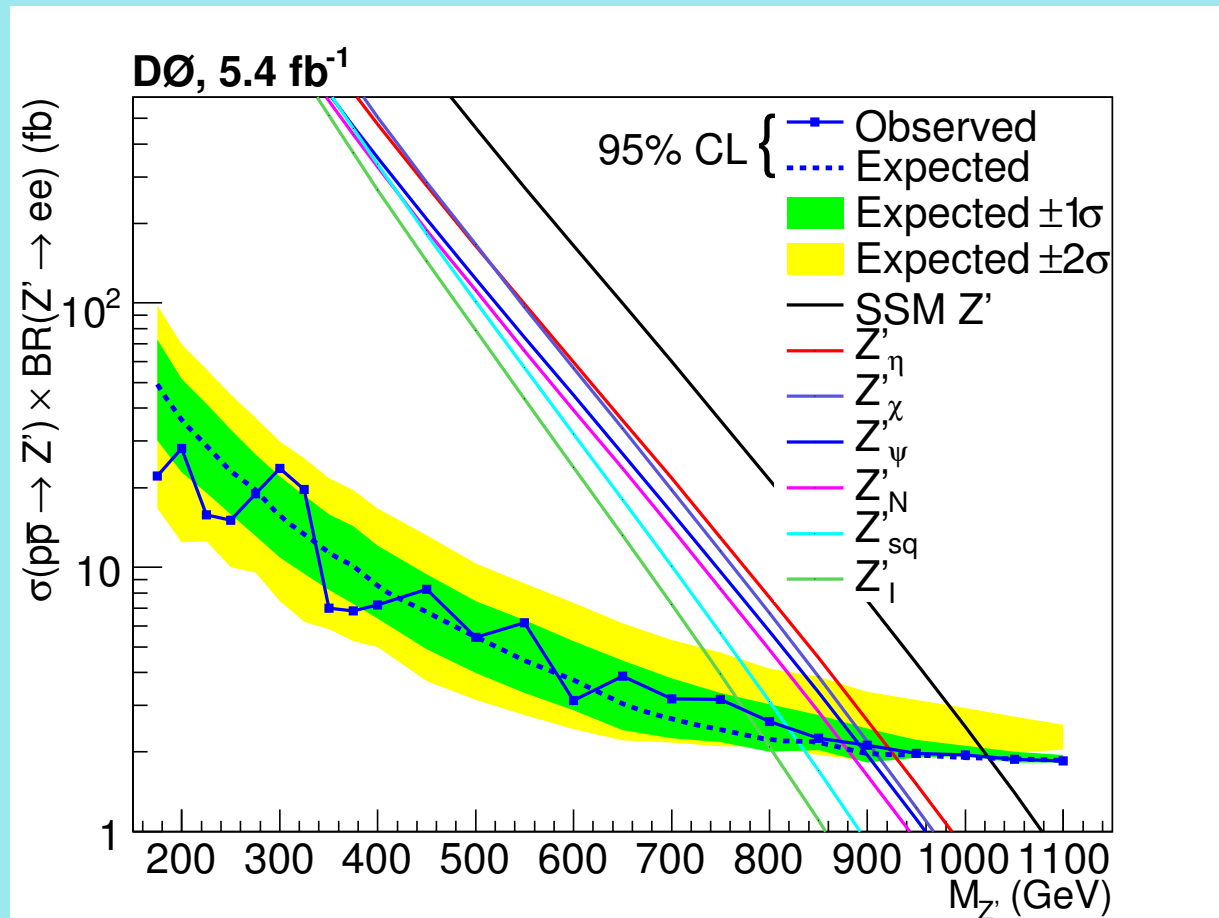
ID Efficiency	3% per object
DY ee NNLO mass dependent k-factor	5%
QCD $\gamma\gamma$ NLO shape mass dependent	$\sim 10\%$
Background Normalization	2% (M_{ee}) 10% ($M_{\gamma\gamma}$)

- * In the absence of a significant excess, proceed with setting a limit at the production cross section times branching ratio at 95% CL as a function of a test mass
- * Use a Poisson log-likelihood ratio (LLR) test statistics

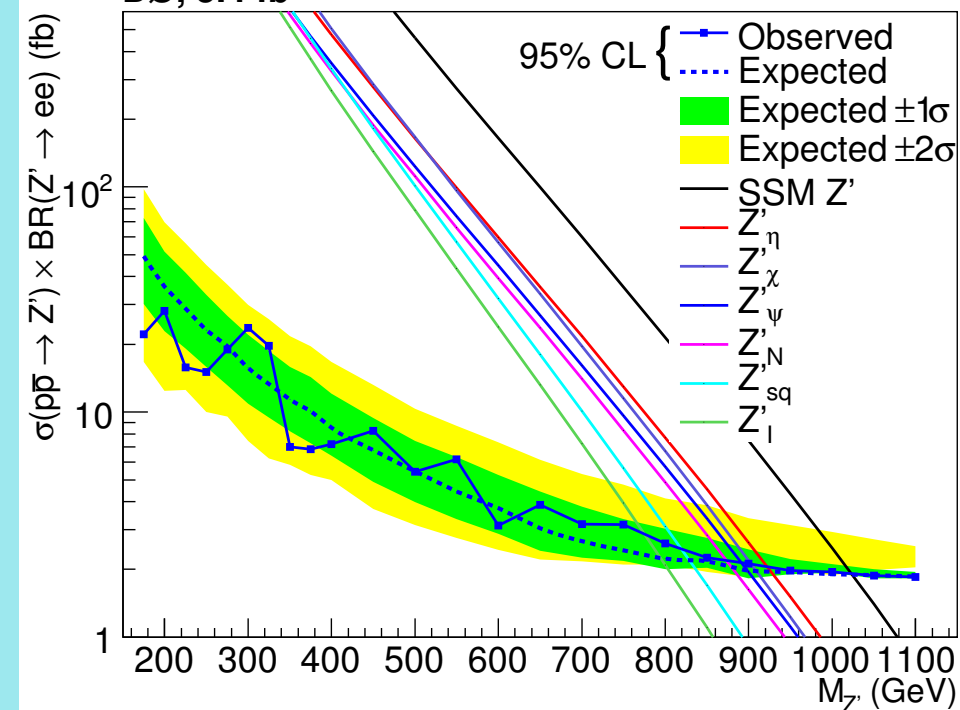


- * In the absence of a significant excess, proceed with setting a limit at the production cross section times branching ratio at 95% CL as a function of a test mass
- * Use a Poisson log-likelihood ratio (LLR) test statistics
- * Interpret limit to a low mass limit for a variety of Z' models

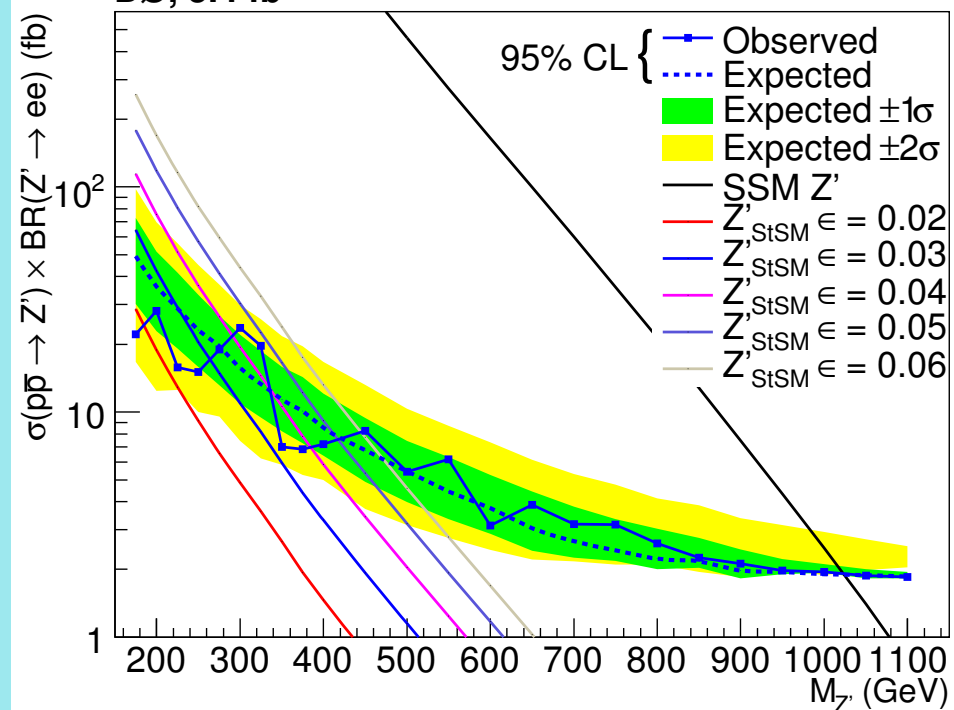
PLB 695,
88 (2011)



DØ, 5.4 fb⁻¹ **PLB 695, 88 (2011)**

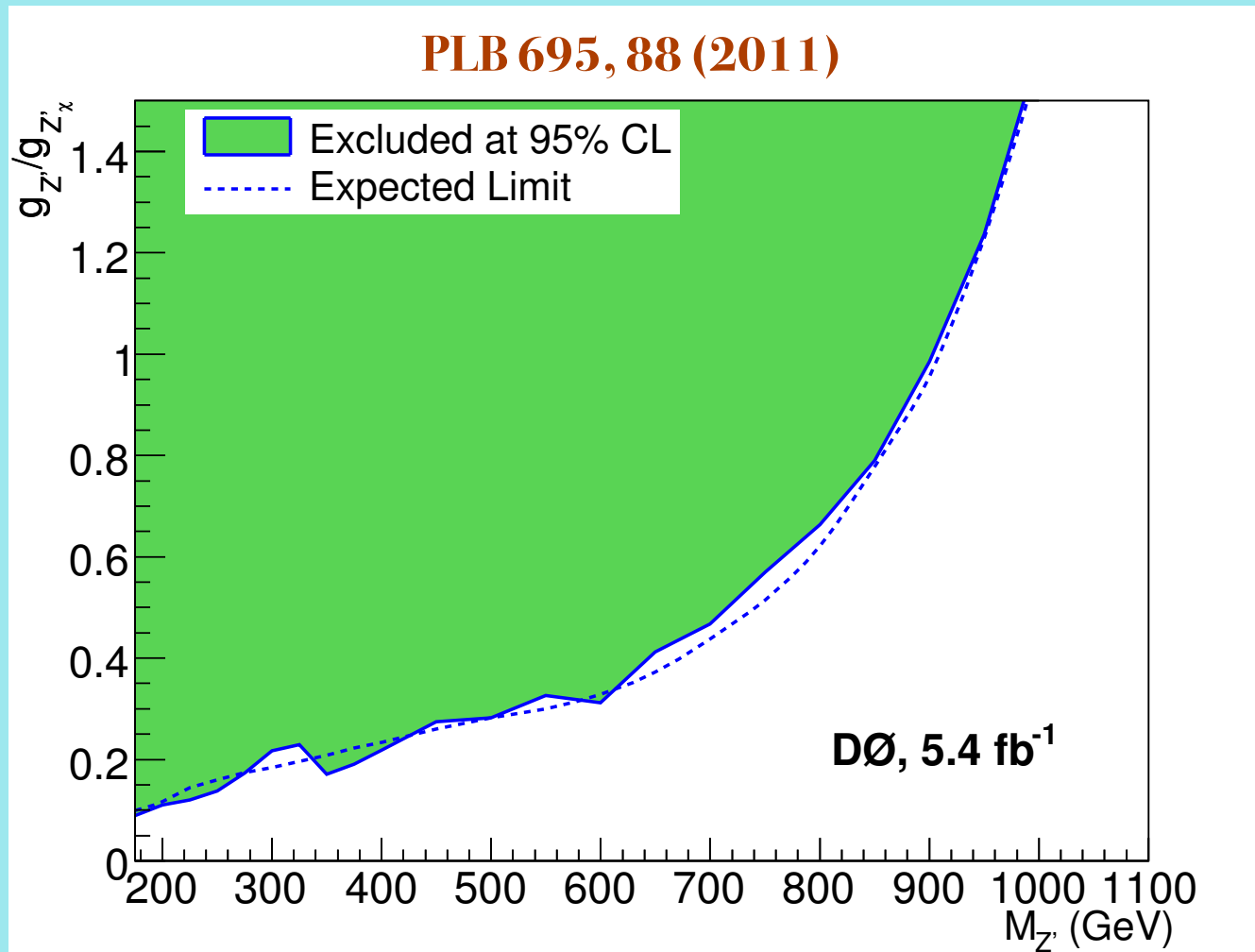


DØ, 5.4 fb⁻¹



Model	Z'_{SSM}	Z'_{η}	Z'_{χ}	Z'_{ψ}	Z'_N	Z'_{sq}	Z'_I
Limit Exp. (GeV)	1024	927	910	898	879	829	795
Limit Obs. (GeV)	1023	923	903	891	874	822	772

Model StSm	$\epsilon = 0.06$	$\epsilon = 0.05$	$\epsilon = 0.04$	$\epsilon = 0.03$	$\epsilon = 0.02$
Limit Exp. (GeV)	471	414	340	227	-
Limit Obs. (GeV)	443	417	289	264	180



- * Couplings for Z' models can be expressed in terms of the $U(1)_{Z'}$ gauge coupling $g_{Z'}$
- * Interpret the 95% CL upper limit on the production $\sigma \times \text{BR}(Z' \rightarrow ee)$ on the $(M_{Z'}, g_{Z'})$ plane for the Z'_χ model. Provides a method of extracting limits for many Z' models.



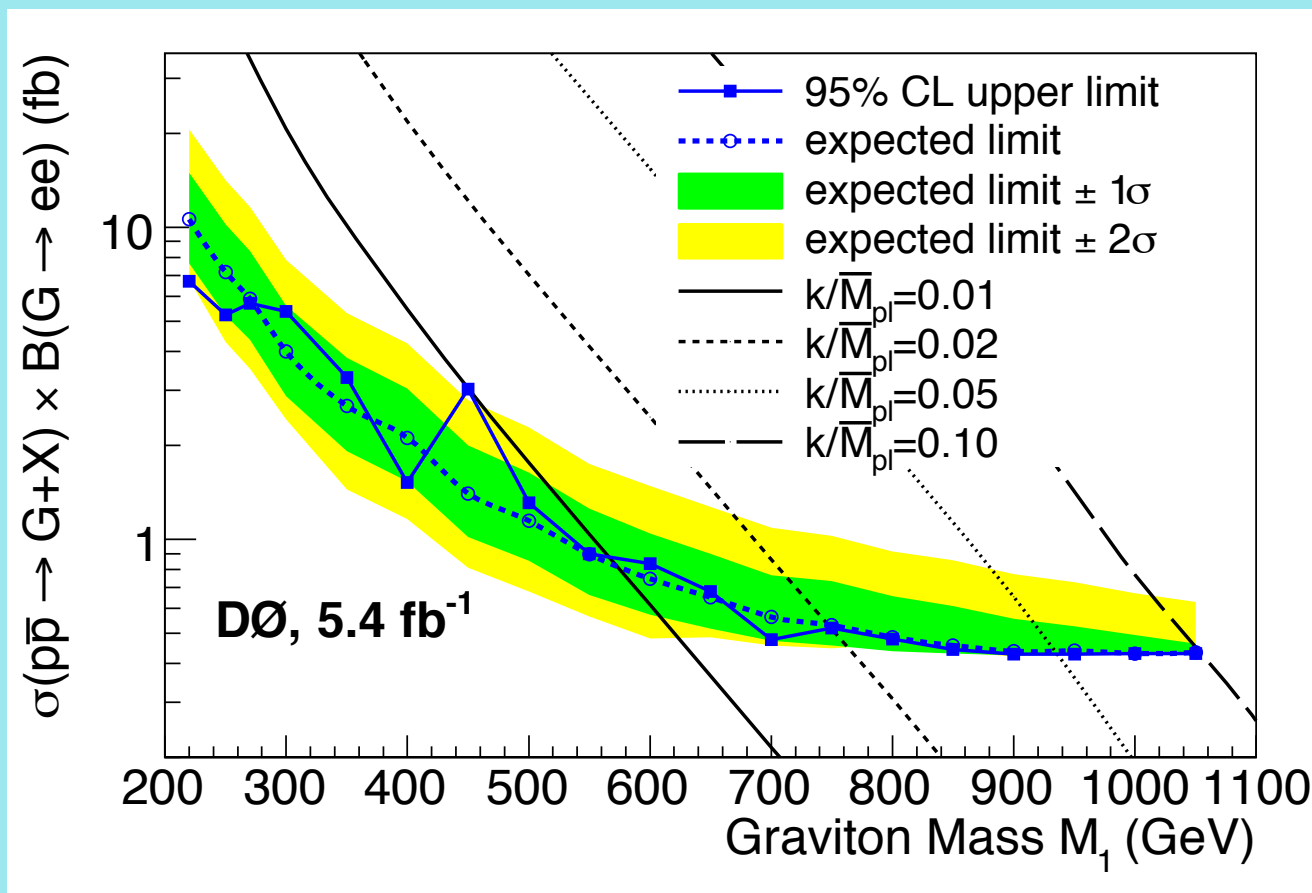
Limit Calculation

Randall - Sundrum Gravitons

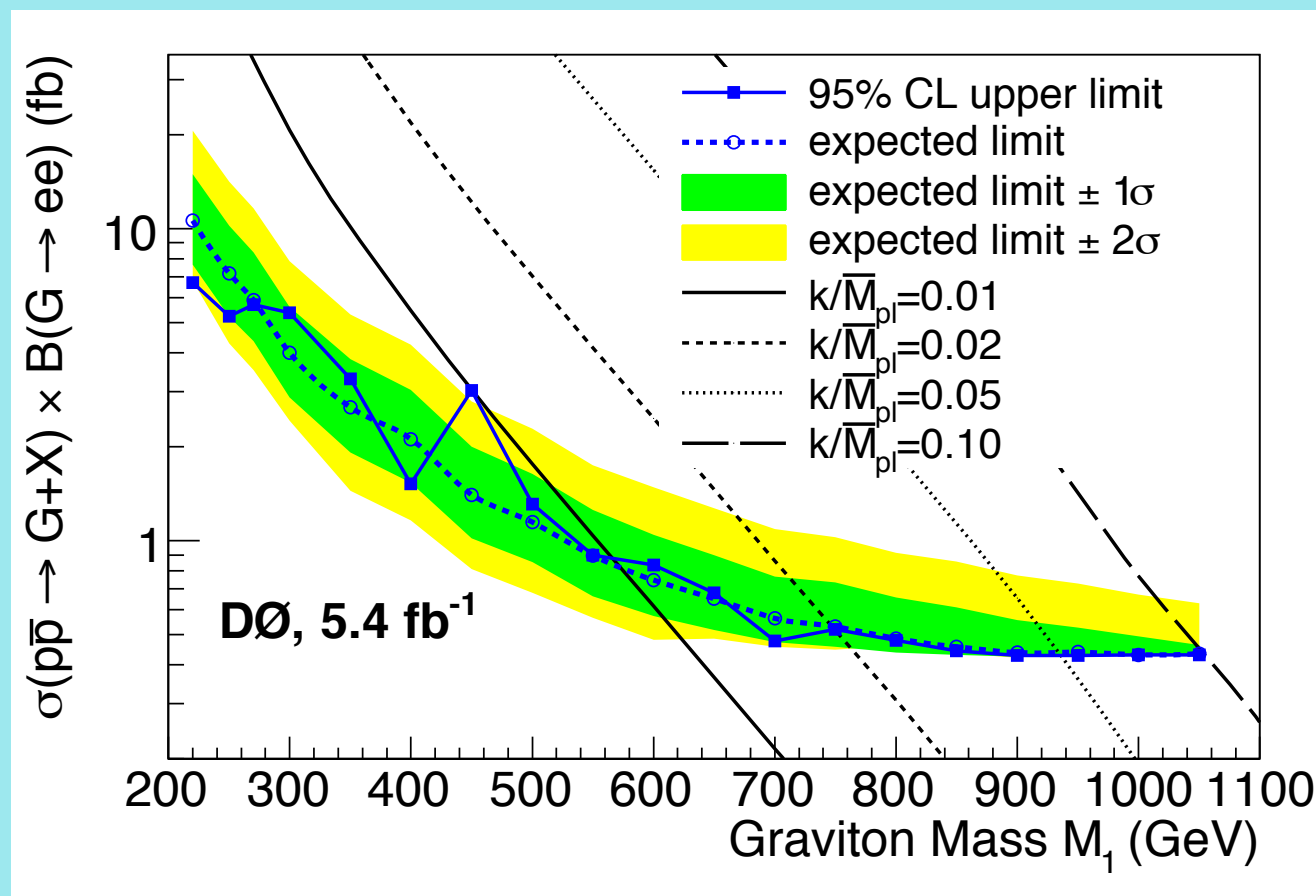


- * In the absence of a significant excess, proceed with setting a limit at the production cross section times branching ratio at 95% CL as a function of a test mass
- * Use a Poisson log-likelihood ratio (LLR) test statistics
- * Interpret limit to a low mass limit for a variety of k/\bar{M}_{Pl} values

PRL 104,
241802 (2010)



Combine ee and $\gamma\gamma$
channels



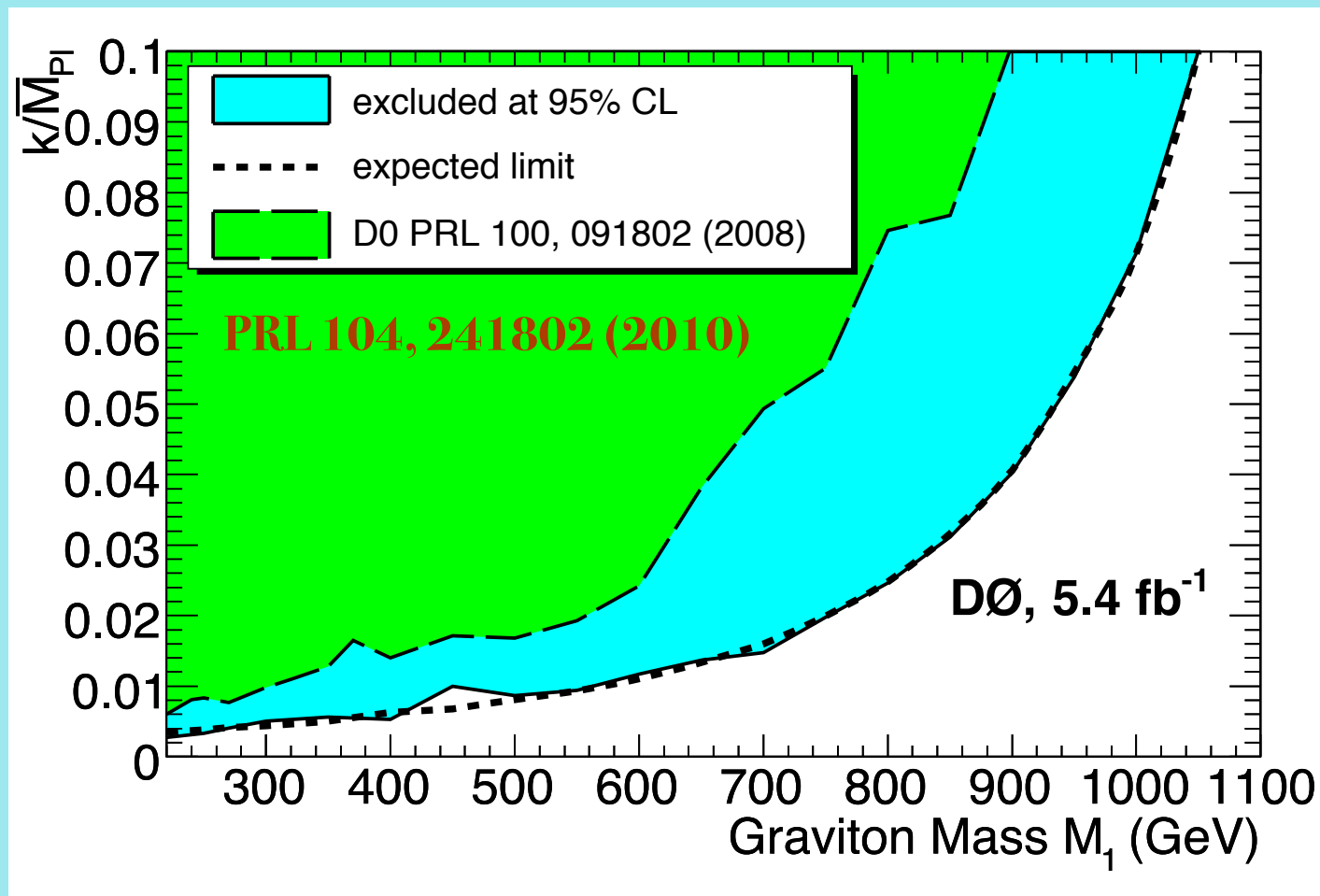
**PRL 104,
241802 (2010)**

Splitting diEM events into ee and $\gamma\gamma$ spectra and tuning the analysis accordingly, provides an improvement of 1.5 - 2 over the increase of integrated luminosity

- * For $k/M_{Pl} = 0.1$, $M_1 < 1040$ GeV region is excluded at 95% CL
- * For $k/M_{Pl} = 0.01$, regions $M_1 < 440$ GeV and $460 < M_1 < 560$ GeV are excluded at 95% CL

Limit Calculation

Randall - Sundrum Gravitons



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SYNOPSIS



Summary and Conclusions



- * Searches for a heavy narrow resonance decaying to ee and/or $\gamma\gamma$ channels, have been performed using 5.4 fb^{-1} of data collected with the DØ detector at the Fermilab Tevatron Collider
- * No evidence of a heavy narrow resonance is observed
- * Set upper limits on the production cross section time the branching ratio at 95% CL
- * Limits are interpreted in the frame of Z' bosons and RS gravitons
 - * Existence of SSM Z' with $M < 1023 \text{ GeV}$ is excluded at 95% CL
 - * *PLB 695, 88 (2011)*
 - * RS Graviton with $M < 1040 \text{ GeV}$ is excluded at 95%CL for coupling of 0.1
 - * *PRL 104, 241802 (2010)*
- * Even-though analysis may be updated with the full data-sample
 - * LHC experiments have already explored new territory at high mass
- * LHC at 14 TeV center-of-mass is expected to search for a Z' up to 5 TeV (higher for a RS Graviton)



BACKUP

Reconstructed di-EM invariant mass distributions for various signal samples

